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# PROCEEDINGS

AMERICAN SOCIETY
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APRIL, 1953

## LAMINAR TO TURBULENT FLOW IN A WIDE OPEN CHANNEL

By W. M. Owen

HYDRAULICS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

# LAMINAR TO TURBULENT FLOW IN A WIDE OPEN CHANNEL

By W. M. Owen[1]

Synopsis

Theoretical equations are presented, involving the velocity and rate of laminar flow in rectangular channels and in channels of infinite width. Data taken at shallow depths on an open channel 1.5 ft wide and 20 ft long are plotted in a graph showing the relation between the friction factor and the Reynolds number. The point of departure of these data from the theoretical laminar flow line is taken to be the critical value of the Reynolds number at which the flow changes from laminar to turbulent. A thread of dye was also injected into the flow to determine whether the flow was laminar, turbulent, or transitional. The two methods of determining the critical velocity gave similar results.

## 1. Introduction

In spite of the extensive literature on the subject of open channel flow, little information is available on laminar flow and the transition from laminar to turbulent flow in open channels. The following quotation from a well-known textbook[2] on fluid mechanics is indicative of the present state of knowledge on this subject:

> "It might, in fact, be inferred from analogy with pipe flow that below some 'critical' velocity the resistance will be proportional to the first power of the velocity. The clear glassy non-distortive reflecting surface observed in any long straight reach of a deep and sluggish stream tends to strengthen this inference, while the behavior of small particles of suspended matter appears to show almost conclusively that at low speed motion takes place in stream lines."

Note.—Written comments are invited for publication; the last discussion should be submitted by October 1, 1953.

[1] Development Engr., Airesearch Mfg. Co., Los Angeles, Calif.

[2] "Hydraulics and Its Applications," by A. H. Gibson, D. Van Nostrand Co., Inc., New York, N. Y., 1930, p. 295.

Observers engaged in the measurements of the discharge of natural streams testified that, from time to time, the method of measuring the discharge based on turbulent flow fails, and that the discharge appears to be varying approximately as the first power of the slope. In 1907, E. C. Thrupp[3] conducted experiments on the Thames and Kennet rivers in England and ascertained that, below an average velocity of 0.64 ft per sec, the velocities were approximately proportional to the slope, and above this velocity, the velocities were approximately proportional to the square root of the slope. Mr. Thrupp reached the conclusion that laminar flow existed below this critical value of the velocity, which would indicate that laminar flow existed at Reynolds numbers of several hundred thousand. If this conclusion is true, the subject of laminar flow in open channels is not merely an academic one but is of vital interest

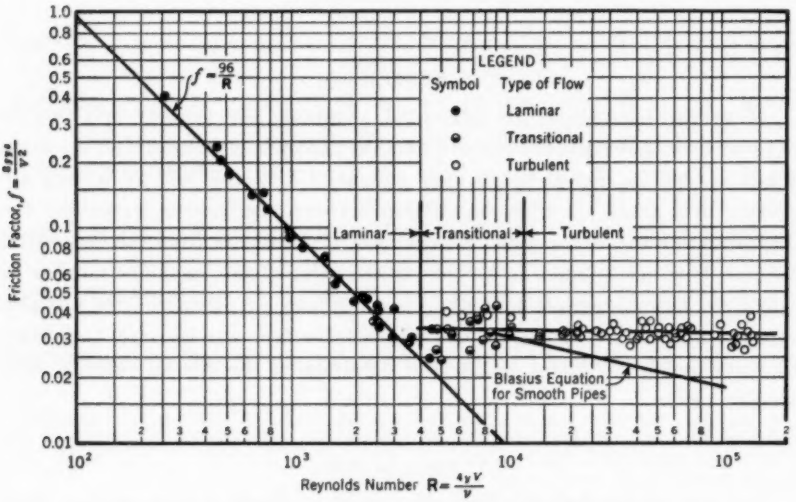


FIG. 1.—RELATION BETWEEN THE FRICTION FACTOR AND THE REYNOLDS NUMBER FOR A WIDE OPEN CHANNEL

to engineers engaged in open channel work. On the other hand, if the critical Reynolds number for open channel flow is the same, or somewhat lower, than that for closed conduits, as indicated by some writers, practically all open channel flow of interest to the hydraulic engineer would occur in the turbulent range, and the subject of laminar flow in open channels would be of little interest to the hydraulic engineer.

The depth of water in the channel used in this investigation (1.5 ft wide) never exceeded 0.3 ft so that the flow conditions in the channel could be considered to approach the conditions of flow in a channel of infinite width. Determination of whether the flow was laminar or turbulent was made by noting both the variation of the resistance law (Fig. 1), and the behavior

[3] "Flowing Water Problems," by E. C. Thrupp, *Proceedings*, Inst. C. E., Vol. 171, London, England, 1907–1908, p. 346.

of a stream of colored water injected into the flow in the manner introduced by Osborne Reynolds.

## 2. Apparatus and Procedure

Fig. 2 is a photograph of the glass-walled flume used in this investigation. The flume consists of a large reservoir containing a gravel baffle, an approach section, and a rectangular glass-walled channel 20 ft long and 1.5 ft wide. The bottom of the channel is made of polished brass plate. The support consists of a roller under the reservoir, about which the entire flume pivots, and threaded posts at the downstream end of the channel. The slope may be changed by turning nuts on the threaded posts by means of a suitable

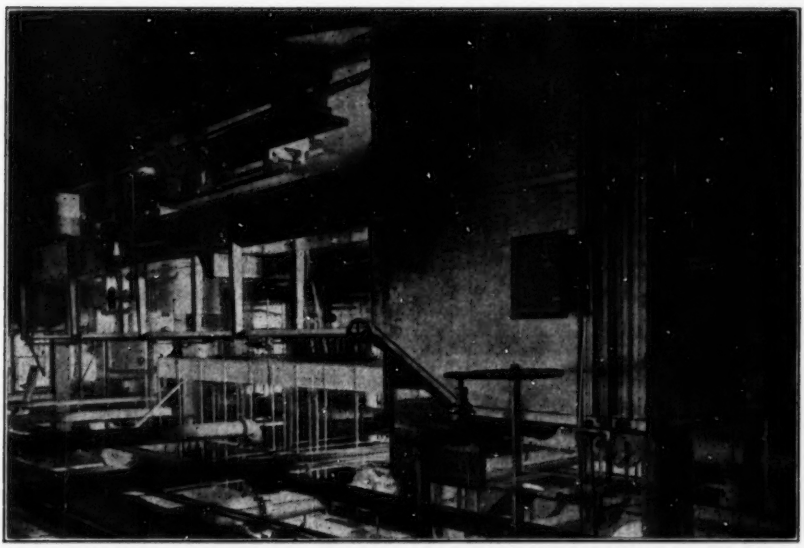

Fig. 2.—Laboratory Arrangement of the Glass-Walled Flume Used in the Investigation

gear train. This channel was leveled carefully by means of a surveyor's instrument before the beginning of the tests. A counter mounted on the shaft of the slope-adjusting wheel was then set at zero, and the slopes for the various tests were determined from the reading of this counter. The bottom was found to be not perfectly flat, showing depressions and elevations in the order of magnitude of 0.01 in. These depressions and elevations may cause serious errors when small slopes and shallow depths are used. Preliminary tests were made to determine the smallest slopes at which consistent data could be taken, and no data appearing in this paper were taken for slopes below this value.

The depth of water in the channel was controlled by a brass end gate. Two electric point gages, 10 ft apart, were used to measure the depth of water in the channel, to the nearest 0.0005 ft. The rate of flow was determined by

measuring the time necessary to collect a given weight of water in a tank mounted on a calibrated scale.

The nature of the flow in the channel was made visible by injecting colored water into the stream through a long glass tube (3 mm, outside diameter) parallel to the direction of the flow. The colored water was made by dissolving a few crystals of potassium permanganate in a beaker of water.

The test procedure was as follows: The channel was set at a given slope, and the tail gate was adjusted to give approximately the desired depth for the test. The supply-control valve was then adjusted until uniform flow was established. The rate of discharge, the depth, and the water temperature were then determined and recorded. Colored water was next introduced into the stream, and the nature of the flow was noted and recorded.

## 3. Derivation of the Theoretical Equations for the Velocity Distribution and the Rate of Flow for Laminar Flow in Open Channels

*General Equations for Laminar Flow in Channels of Rectangular Cross Section.*—In deriving the following relationships, use will be made of the fact

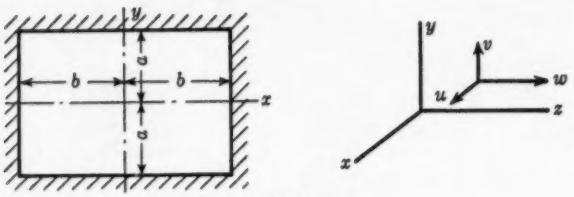


Fig. 3

that the theoretical flow characteristics, such as velocity distribution and energy loss for an open channel of depth $a$ and width $2\,b$ (Fig. 3), are exactly the same as those of one half of a closed conduit of depth $2\,a$ and width $2\,b$. The use of this fact simplifies the problem considerably, inasmuch as the boundary conditions are the same for all sides. The following equations are valid for all rectangular conduits and channels, subject to the restriction that depth $a$ in the following equations must always be one half of the length of the shorter side.

The Navier-Stokes equations for this case reduce to

$$\nu\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}\right)=-g\frac{\partial H}{\partial z}=-g\,S=\text{Constant}\qquad(1)$$

or

$$\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}=-\frac{g\,S}{\nu}=-\text{K}\qquad(2)$$

in which $S$ is the slope of the channel, $\nu$ is the kinematic viscosity, and $g$ is the acceleration of gravity. The boundary conditions are as follows: When

$$y=\pm a;\qquad \omega=0$$

and when

$$x=\pm b;\qquad \omega=0.$$

Eq. 2 is of the same form as the differential equation obtained in the problem of torsion of rectangular bars. The solution of this equation has been found, by S. Timoshenko,[4] to be

$$\omega = \frac{16\,K\,b^2}{\pi^3} \sum_{n=1,3,5}^{\infty} \frac{1}{n^3} (-1)^{(n-1)/2} \left( 1 - \frac{\cosh \frac{n\,\pi\,x}{2\,b}}{\frac{n\,\pi\,a}{2\,b}} \right) \cos \frac{n\,\pi\,x}{2\,b} \quad \ldots\ldots (3)$$

Eq. 3 gives the velocity at any point of the cross section. The rate of flow, $Q$, in an open channel of depth $a$ and width $2\,b$ may be determined from the following equation:

$$Q = \int_{-b}^{b} \int_{o}^{a} \omega \, dx \, dy \quad \ldots\ldots (4)$$

The solution of this equation has been found, by Mr. Timoshenko, to be

$$Q = \frac{2}{3} K\,b^3\,a \left( 1 - \frac{192\,b}{\pi^5\,a} \sum_{n=1,3,5}^{\infty} \frac{1}{n^5} \tanh \frac{\pi\,n\,a}{2\,b} \right) \quad \ldots\ldots (5)$$

*Derivation of the Theoretical Expression for the Friction Factor for Laminar Flow in a Channel of Infinite Width.*—The following expressions for laminar flow in a channel of infinite width were given by Robert E. Horton, M. ASCE, H. R. Leach, A.M. ASCE, and R. Van Vliet,[5] M. ASCE. The velocity distribution $\omega$ is given by

$$\omega = \frac{g\,S}{2\,\nu} (a^2 - y^2) \quad \ldots\ldots (6)$$

the rate of flow per unit width by

$$q = \int_{-a}^{a} \omega \, dy = \frac{g\,S\,a^3}{3\,\nu} \quad \ldots\ldots (7)$$

and, the average velocity, $V$, is equal to

$$V = \frac{q}{A} = \frac{g\,S\,a^2}{3\,\nu} \quad \ldots\ldots (8)$$

The Darcy equation for uniform flow in an open channel may be written as

$$S = \frac{f}{4\,\mathbf{R}} \frac{V^2}{2\,g} \quad \ldots\ldots (9)$$

in which $f$ is the friction factor and $\mathbf{R}$ is the Reynolds number.

The characteristic dimension used is four times the hydraulic radius, so that the friction factors obtained will be comparable to those found for flow in pipes, using the diameter as the characteristic length. On substituting

[4] "Theory of Elasticity," by S. Timoshenko, McGraw-Hill Book Co., Inc., New York, N. Y., 1934.

[5] "Laminar Sheet Flow," by Robert E. Horton, H. R. Leach, and R. Van Vliet, *Transactions*, Am. Geophysical Union, 1933–1934, pp. 393–404.

Eq. 7 into Eq. 8, and simplifying,

$$f = \frac{24\,\nu}{q} \qquad (10)$$

For two-dimensional flow $\overline{R} = 4\frac{q}{\nu}$, and

$$f = \frac{96}{\overline{R}} \qquad (11)$$

A plot of this equation is shown along with the experimental data in Fig. 1.

General reading references in support of the theoretical parts of this paper are to be found in the works of A. H. Gibson[2]; Mr. Thrupp[3]; Mr. Timoshenko[4]; Messrs. Horton, Leach, and Van Vliet[5]; Lorenz G. Straub[6]; J. Allen[7]; R. J. Cornish[8]; L. Hopf[9]; H. Jefferys[10]; H. Levy[11]; and in "Some Experiments on Shallow Flows Over a Grassed Slope," presented[12] in 1939.

## 4. Experimental Results

The results of the experimental part of this investigation are summarized in Fig. 1, showing the relation between the friction factor and the Reynolds number plotted to logarithmic scales. The theoretical relationship for two-dimensional flow and Blasius' empirical relation for turbulent flow in smooth pipes is shown in addition to the experimental data. The data depicted by the solid circles are for test runs in which the thread of dyed water injected into the stream maintained a straight unbroken line for the entire length of the channel. The data designated by the half-solid circles are for test runs in which the dye thread was observed to oscillate but remained intact. The data shown by the open circles are for test runs in which the dye thread was observed to break up and to disclose the presence of vortices.

The critical Reynolds number is taken to be the value of the Reynolds number at which the average curve through the experimental data first departs from the theoretical curve for laminar flow. From the graph, the critical Reynolds number appears to be approximately 4,000.

The data near the critical Reynolds number were taken for both increasing (that is, laminar to turbulent) and decreasing (that is, turbulent to laminar) Reynolds numbers. No difference in the value of the critical Reynolds number was found for the two conditions. This result is believed to be caused by the fact that initial disturbance in the water was such that the upper and lower critical Reynolds numbers coincided.

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[6] "Studies of the Transition Region Between Laminar and Turbulent Flow in Open Channels," by Lorenz G. Straub, *Transactions*, Am. Geophysical Union, 1939, pp. 649–653.

[7] "Streamline and Turbulent Flow in Open Channels," by J. Allen, *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Vol. 17, No. 116, June, 1934, pp. 1081–1112.

[8] "Flow in a Pipe of Rectangular Cross-Section," by R. J. Cornish, *Proceedings*, Royal Soc. of London, Series A, Vol. 120, 1928, pp. 691–695.

[9] "Turbulenz bei einen Flusse," by L. Hopf, *Annalen der Physik*, Vol. 32, Sect. 4, April–July, 1910, pp. 777–808.

[10] "Flow of Water in an Inclined Channel of Rectangular Section," by H. Jefferys, *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Vol. 49, No. 293, May, 1925, pp. 793–807.

[11] "On the Criterion for Stable Flow of a Fluid in a Uniform Channel," by H. Levy, *Proceedings*, Royal Soc. of Edinburgh, Vol. 41, Pt. 2, 1920–1921, pp. 136–147.

[12] "Some Experiments on Shallow Flows over a Grassed Slope," *Transactions*, Am. Geophysical Union, Pt. IV, 1939, pp. 653–656.

The "dip" in the curve and the scatter of data which characterize the transition region in the Stanton diagram for flow in pipes are also present in the data shown in Fig. 1.

The Blasius empirical relation is shown in Fig. 1, so that a comparison in the turbulent flow range of the friction factors for smooth pipes and the experimental data for the smooth channel used in this investigation might be made. The data from this investigation agree with the Blasius equation only for a small range of values in the transition region. The experimental data presented show an almost constant friction factor in the turbulent flow range, which is characteristic of the type of curve obtained for pipes of considerable roughness. The increasing degree of scatter, with increasing Reynolds numbers, may be explained by the fact that surface waves present at the higher values of Reynolds number made it difficult to determine depths in the channel.

## 5. Conclusion

From the results of this investigation, four general conclusions can be drawn concerning laminar flow and the transitions from laminar to turbulent flow, as applied to the flow of water in a wide open channel:

1. In the laminar range, the curve showing the relationship between the friction factor and the Reynolds number agrees well with the theoretical equation derived from the Navier-Stokes equations in Section 3 of this paper.
2. The value of the Reynolds number at which the flow first departs from the laminar state is approximately 4,000.
3. There is a transition from laminar to turbulent flow, which extends, approximately, from a Reynolds number of 4,000 to 11,000, in which the flow is neither truly laminar nor turbulent. There is considerable uncertainty as to the value of the friction factor in this range.
4. The data presented in this paper for the turbulent flow range are not in agreement with the smooth pipe curve of Blasius, but rather show an almost constant value of the friction factor.

*Comment.*—From the evidence presented herein, it would appear that it is unlikely that laminar flow would exist in large natural streams. The fact that the surface of the stream exhibits a smooth glassy surface as noted by several writers, is no indication that the flow is laminar; possibly, it indicates that only the surface velocity is lower than that necessary for capillary waves to form. Laminar open channel flow is known to exist in nature, however, with the flow of thin sheets of water over the surface of the ground.

The information contained in this paper may be of importance in the study of models of natural open channels. The rates of flow and the dimensions of the model are such that the Reynolds numbers frequently fall in the laminar or transitional range, as determined in this investigation. The fact that the flow in the prototype is turbulent, whereas that in the model may be either laminar or transitional, may be one cause of the difficulty in the verification of models.

ACKNOWLEDGMENT

This investigation was conducted in the Hydraulics Laboratory of the Department of Theoretical and Applied Mechanics, as a part of the work of the Engineering Experiment Station of the University of Illinois, at Urbana.

Acknowledgment is due H. L. Langhaar for his able assistance in the theoretical part of this paper, and to W. M. Lansford, M. ASCE, under whose direction a preliminary investigation was performed as a thesis project.

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